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Methods of creating and using a digital twin of a mobile transport and transshipment rope complex

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Introduction. The paper considers the creation and application of digital twins at various stages of the life cycle of mobile transport and transshipment rope complexes (mobile ropeways), the equipment of which is mounted on the basis of wheeled or tracked chassis of high load capacity. The work objective is to improve safety in using such transport systems based on real-time forecasting of potential failures. This will prevent the occurrence of emergencies in a timely manner.

Materials and Methods. The structure of the digital twin of the mobile transport and transshipment rope complex is proposed. Approaches to the analysis of ongoing work processes in order to prevent accidents have been developed. They are based on simulation modeling of the system dynamics using new complex mathematical models built through the system approach.

Results. The developed method was tested on a large-scale layout of a mobile transport and transshipment rope complex created by 3D printing methods. A mathematical model of this system was developed; it was used to construct a digital double of the experimental model. The possibility of predicting failures in the layout is shown experimentally through the example of a rope slipping case. To do this, the actual value of the load suspension point coordinate obtained through the video stream processing method was compared to the predicted value calculated using a digital twin.

Discussion and Conclusions. The research results provide the creation of an industrial digital twin of a mobile transport and transshipment rope complex mounted on cross-country wheeled chassis.

Keywords: ropeway, mobile complex, suspension of load, digital twin, creation, applying.

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Introduction. Concepts for creating a new generation of ropeway transport systems are proposed. These include urban passenger ropeway transport systems based on the “Rope Metro” technology [1, 2], and mobile transport and reloading ropeway complexes (MTRRC) [2-5]. The complex (Fig. 1) represents several base stations of the cable way whose equipment is mounted on mobile chassis.

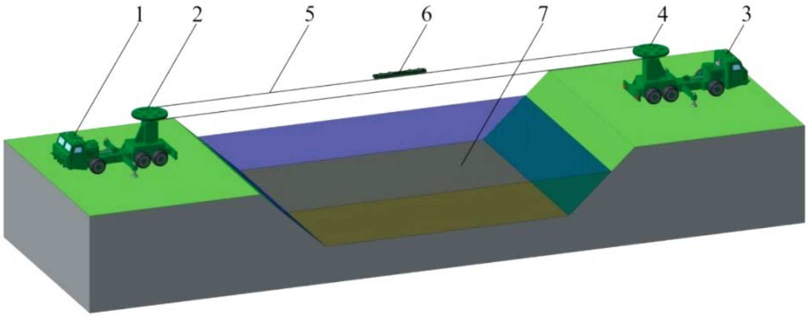

Fig. 1. Conception of mobile transport and reloading cable system [2, 6]:
1 – drive base station on the basis of wheeled chassis; 2 – drive pulley; 3 – non-drive base station; 4 – non-drive pulley with cable rope tensioner; 5 – ring traction and drive rope; 6 – carriage for suspension of cargo; 7 – overcome barrier

For successful implementation of this idea, it is required to develop a scientific basis for studying work processes and design of MTRRC. At the same time, it is necessary to solve scientific and technical problems of providing the overall stability of base stations, installation and tension of the rope system, loading and unloading of the ropeway [2].

In the context of digitalization of the industrial production, it is required to develop high-precision digital twins of the MTRRC, which enable to create effective and globally competitive product samples.

Materials and Methods. Active development of system digital models, which can be considered the prototype of digital twins, started with the introduction of computer-aided design systems that support the basic stages of the life cycle of an industrial product. The relationship between the stages of the life cycle and the main types of computer-aided design systems is widely known (Fig. 2) [7].

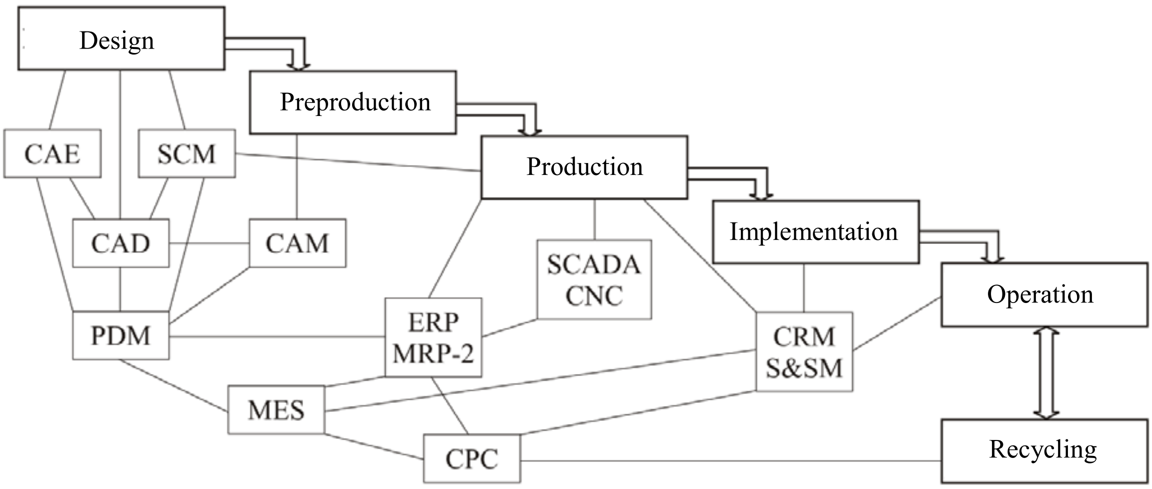

Fig. 2. Relationship between stages of industrial product life cycle and main computer-aided design systems

The creation of a system digital model starts with the definition of the configuration (geometry) of the object in the CAD system. Then, the required calculations of the dynamics, strength, stability, performance of the designed object, are performed in CAE systems; while process documentation is developed, and programs for machine tools with numerical control are prepared in CAM systems. SCM systems allow us to consider the possibility of using purchased products during design and to provide their timely delivery at the production stage. The indicated CAD systems are integrated at the level of PDM systems that control the design and preproduction processes. In the production shops, SCADA systems provide operation dispatching, and CNC systems control technological equipment including numerically controlled machines. The last two systems are integrated at the level of the MES-system that controls production processes. ERP and MRP-2 systems provide the enterprise with the desired resources. At the stage of implementation and operation, interaction with consumers is carried out using CRM-systems of sales and S&SM-

systems of maintenance and repair. Integration of all of these systems forms the basis of digital business (CPC), which is also called digital enterprise [7].

The analysis of the circuit (Fig. 2) shows that existing digital twins of industrial products have the greatest refinement when used at the design and production stages. At this, the work processes occurring at the stage of operation of an industrial product are considered in the design in terms of initial data presented in the form of numerical values or distribution laws. Foremost, such data include external loads and other influences, sequences of working operations. Under this approach [7], after manufacturing, an industrial product becomes a commodity for which not technical, but economic properties are more important: sales volumes, price, quantity and nature of claims for warranty service, customer reviews, and parameters of purchase and sale documents. Therefore, during the operation phase, detailed digital twins developed during design and production are usually not used. They can be used for overhaul or modernization of an industrial product, but in this case, it is taken out of service and returned to the manufacturer or a specialized repair company. This conclusion is also confirmed by the fact that 11 out of 14 computer-aided design systems presented in Fig. 2 are related to design and manufacture.

In the context of digitalization of the industrial production, such an approach is insufficient since the manufacturer of industrial products does not have the needed data to improve the design, control algorithms and technology for manufacturing competitive products and the consumer does not have complete information on the product in use. At the same time, mainstreaming of digital twins at the stage of operation of an industrial product will allow solving two main problems:

— operational challenge is to take into account possible abnormal and emergency conditions that should be avoided under the operation of the finished product;

— project designing task is focused on the creation of new structures and algorithms for program control considering the array of statistical data and mathematical models formed under the operation of industrial products.

At the same time, constant updating of the digital twin of the object under operation plays a key role. Thus, it is required to use the developed high-precision digital twins at all stages of the life cycle of an industrial product [8, 9].

For this, the developed mathematical models that underlie the digital twin are processed in real time on high-speed computers. Signals from sensors installed on a real object are used as initial data for the calculation (Fig. 3). The digital twin is linked to a real object through a cloud service.

This approach enables to increase the efficiency and safety of the industrial product operation, reveal hidden phenomena and effects, collect material for further modernization and improve consumer qualities, and prevent emergencies [8, 9].

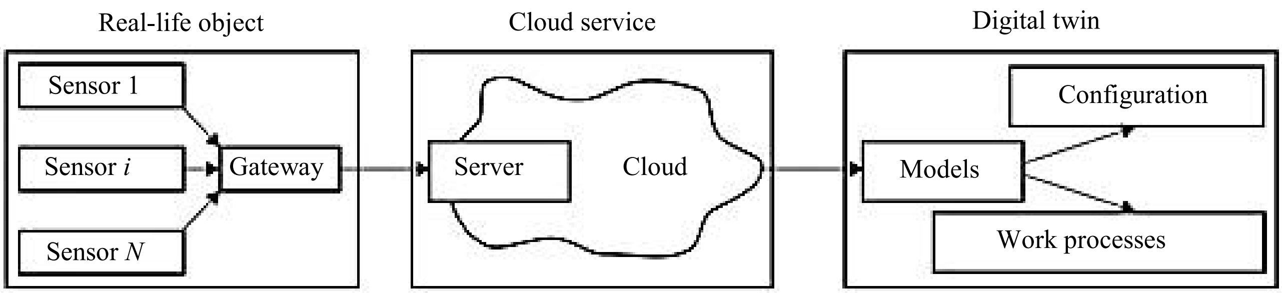

Fig. 3. Relationship between an industrial product and its digital twin

Thus, a digital twin is a software analogue of a physical device (industrial product) that simulates in real time the internal processes, technical characteristics and behavior of the device under the impact of random actions and the environment whose parameters are transmitted from the sensors of a real device operating in parallel [8, 9]. The digital

twin contains mathematical models of the object's configuration and workflows. In this case, the dimensions and characteristics of the configuration are used to calculate the initial parameters of mathematical models that describe work processes. For example, the inertia moment of a mechanism element is calculated on the basis of its geometric model. Then, the obtained value of the moment of inertia is translated into the differential equation of motion of the element.

To construct mathematical models of the industrial product workflows, it is recommended to use a systematic approach [10], according to which each significant element of the system is associated with a mathematical submodel assigned to submodels of other elements through joint parameters and communication equations. This approach provides the creation of easy-to-use modular mathematical models with account for the feedbacks between system elements.

This paper considers the creation and use of a digital twin of a mobile transport and transshipment rope complex at the stage of operation. Other stages of the MTRRC life cycle are not considered since they use general approaches that are applied for any machinery and equipment. It is believed that for the development of a digital twin, there are complete sets of three-dimensional computer geometric models of the MTRRC and design-engineering documentation developed at the design and preproduction stage.

Let us consider the options for using a digital twin to prevent emergencies under the operation of a mobile transport and transshipment rope complex. Let $\{a\}$ be the vector of parameters of a real-life object obtained by means of objective control means (sensors connected to measuring systems). These parameters describe the current state of the MTRRC and the nature of the ongoing work processes at the current time moment t_i. The values of the parameters $\{a\}$ are determined periodically, within a given period Δt. The parameters obtained from the physical object correspond to the parameters $\{x\}$ calculated using the mathematical model. The results of modeling work processes are written into the matrix [X], which contains information on the change in the simulated parameters over time. The parameters are simulated using various step-by-step numerical methods while the size of the computation step by the model time t_m is equal to Δt_m.

The parameters $\{a\}$ at each current moment of time t_i are transferred to the mathematical model input, with the help of which the modeling of the MTRRC work processes for a given period of time T is carried out. Besides, information on the configuration (structure) of a real-time object is used in the calculation. As a result of the calculation in real time, the values [X] are obtained, and according to the results of their analysis, an assessment (forecast) of the possibility of an emergency occurs. If the onset of an emergency is predicted according to the simulation results, the MTRRC immediately stops, or other measures are taken to prevent the accident.

The relationship between a real-time object and a digital twin is clearly illustrated in Fig. 4.

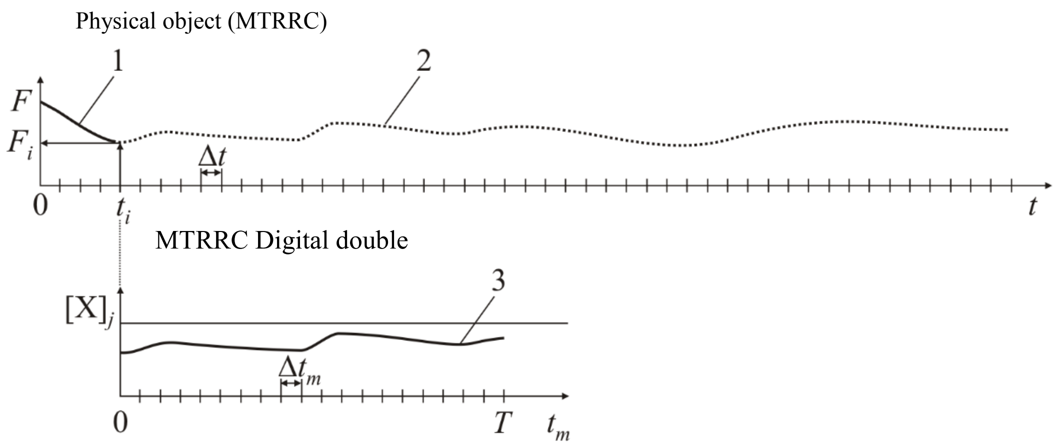

Fig. 4. Implementation of workflow parameter change obtained using objective control of real-time object and digital double: 1 – actual parameter change before t_i, 2 – actual parameter change of real-time object in future; 3 – result of modeling parameter change in future using digital double

One of the parameters of the vector $\{a\}$, for example, the tension force of the carrying rope F, is determined using a force-measuring transducer at intervals Δt. In real time, the tensile force is F_i. Similarly, other components a_i of the vector $\{a\}$, which are transferred for analysis through a digital twin, are determined.

The j-th row of the matrix [X] corresponds to the tension force. If, according to the results of modeling the working processes of MTRRC, the possibility of an emergency is not established, then the work of MTRRC does not

stop. At the next iteration, at time $t_i + \Delta t$, new values of the vector $\{a\}$ are determined, after which a new simulation session is performed. In the event of a negative forecast, for example, if the calculated tensile force exceeds the permissible value, then the operation of the MTRRC stops until the reasons are identified and the threat of an emergency is eliminated.

To improve the accuracy of the forecast, it is required to use adequate mathematical models. The deviation of the simulation result (section 3 in Fig. 4) from the actual behavior of the object (section 2 in Fig. 4) can serve as an accuracy criterion. Ideally, the forecast for changes in parameters should fully coincide with the actual change in parameters in future.

In the course of the study, a complex mathematical model being the basis for the MTRRC digital twin [10] was used. The equations of motion included in this model can be written in general form as follows:

$$\begin{cases} [M]\{\ddot{x}\} + [B]\{\dot{x}\} + [C]\{x\} = \{P\}, \\ [Y] = \{0\}, \end{cases}$$

where $\{x\}$ is the vector of laws of motion of system elements (changes in their coordinates in time); $\{\dot{x}\}$ is the velocity vector of system elements; $\{\ddot{x}\}$ is the vector of accelerations of system elements; $[M]$ is the matrix of inertial parameters depending on the masses and moments of inertia of the system elements; $[B]$ is the matrix of dissipation coefficients; $[C]$ is the elastic matrix depending on the rigidity of the system elements; $\{P\}$ is the vector of external loads on the system elements; $[Y]$ is the matrix of algebraic equations for the system parameters association:

$$F_i = F\left(\{x\}, \{\dot{x}\}, \{\ddot{x}\}\right) \text{ [10].}$$

The considered approach enables to predict and prevent the onset of emergencies:

— cable break due to excess driving force;

— rope coming off the pulley;

— fall of the base station due to loss of overall stability;

—the cable car drive stop with self-swinging;

— detachment of the ropeway cab with rolling down the rope and collision with another cab or support;

— impact of the cab on the support or base station equipment;

— heavy side roll when exposed to wind

Research Results. As discussed, the digital twin should interact with a physical object. However, mobile transport and transshipping rope complexes are a promising type of transport systems; so, there are no full-scale experimental prototypes nowadays. At this stage of research, a full-scale model of the MTRRC was created to work out the technique for creating a digital twin. Data on its operation was transmitted to the input of the digital twin. The prototype version of the complex made on the basis of the Engineering Research and Educational Center of Digital Technologies "Industry 4.0" of Ivan Petrovsky Bryansk State University is shown in Fig. 5.

The coordinate of the load suspension point *z* was chosen as the controlled parameter. The coordinate center is located on the axis of rotation of the drive pulley, and the coordinate axis connects the centers of the ropeway pulleys. The current coordinate value on a real-time object was determined using the Kinovea software, which provides analyzing video data.

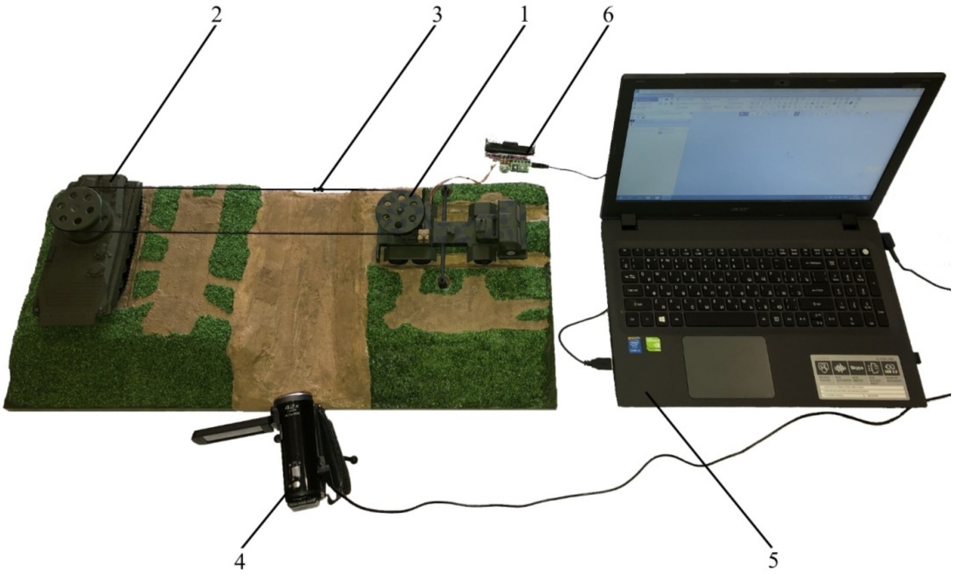

Fig. 5. Full scale mock-up of mobile ropeway complex: 1 – drive base station; 2 – non-drive base station; 3 – suspended load; 4 – videocamera; 5 – laptop computer for signal processing and simulation; 6 – control module based on a microcontroller

The predicted coordinate of the load suspension point was calculated using the model shown in Fig. 6.

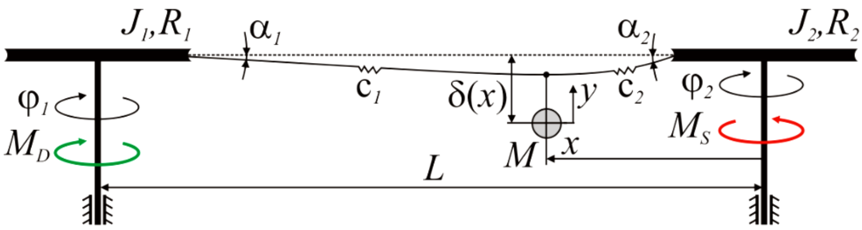

Fig. 6. Computational model to study work processes of the mock-up

At the stage of the rope system acceleration, when the speed of the load $\dot{x}$ is less than the nominal value load $x_{ном}$ = 0.013 m/s corresponding to steady motion, the equations of motion of the elements of the system are as follows:

$$\begin{cases} J_1\ddot{\phi}_1 + c_1\left(\phi_1 - \dfrac{x}{R_1\cos\alpha_1} + \left(\delta(x) - y\right)\dfrac{\sin\alpha_1}{R_1}\right)\cos\alpha_1 = M_D(\dot{\phi}_1); \\ J_2\ddot{\phi}_2 - c_2\left(\phi_2 - \dfrac{x}{R_2\cos\alpha_2} + \left(\delta(x) - y\right)\dfrac{\sin\alpha_2}{R_2}\right)\cos\phi_2 = -M_S(\dot{\phi}_2); \\ M\ddot{x} - c_1\left(R_1\phi_1 - \dfrac{x}{\cos\alpha_1} + \left(\delta(x) - y\right)\sin\alpha_1\right)\cos\alpha_1 - \\ -c_2\left(R_2\phi_2 - \dfrac{x}{\cos\alpha_2} + \left(\delta(x) - y\right)\sin\alpha_2\right)\cos\alpha_2 = 0; \\ M\ddot{y} + c_1\left(R_1\phi_1 - \dfrac{x}{\cos\alpha_1} + \left(\delta(x) - y\right)\sin\alpha_1\right)\sin\alpha_1 - \\ -c_2\left(R_2\phi_2 - \dfrac{x}{\cos\alpha_2} + \left(\delta(x) - y\right)\sin\alpha_2\right)\sin\alpha_2 = -9{,}81M, \end{cases}$$

where ϕ_1, J_1 angle of rotation, inertia moment of the head pulley, respectively; ϕ_2, J_2 are angle of rotation, inertia moment of the tail pulley, respectively; x, y are horizontal, vertical coordinates of the load, respectively; M is load weight; c_1 and c_2 is rigidity of the rope in the area of the head and tail pulley, respectively; α_1 and α_2 are angles of inclination of the rope in the area of the head and tail pulley, respectively; R_1 and R_2 are radii of the head and tail pulley, respectively; L is the distance between the axes of rotation of the pulleys (a span of the ropeway).

Inclination angles of rope branches:

$$\alpha_1 = \alpha_1(x) = a\sin\left(\frac{\delta(x)}{x}\right) \text{ at } x \neq 0,\ \alpha_1 = 0 \text{ at } x = 0;$$

$$\alpha_2 = \alpha_2(x) = a\sin\left(\frac{\delta(x)}{L-x}\right) \text{ at } x \neq 0,\ \alpha_2 = 0 \text{ at } x = L,$$

where the dependence of the rope curve on the position of the load in the span of the ropeway is determined on a full-scale model and has the following form:

$$\delta(x) = 0.003\sin(\pi x / L) \text{ м}.$$

Stiffness of the model elements are determined as follows:

$$c_{x1} = c_{x2} = 100 \text{ N/m};\ c_1 = c_{x1} / R_1;\ c_2 = c_{x2} / R_2.$$

Here are the values of other parameters of the model: $J_1 = J_2 = 0.059$ kgm; $M = 0.025$ kg; $L = 0.395$ m; $R_1 = R_2 = 0.03$ m; $M_D = 34.3 \cdot 10^{-3}$ Nm; $M_S = 0.15 \cdot 10^{-3}$ Nm.

At the stage of steady motion, the law of motion is used:

$$x = x_0 + x_{ном}t,$$

where x_0 is the coordinate of the position of the load corresponding to the end of the transient process and the beginning of the steady motion.

Fig. 7 shows the real-time motion path of the load suspension point and the results of its simulation using a digital twin. In the case of a forced stop of the rope system by keeping the load, the actual position of the load deviated from the predicted one using the digital twin. This fact was recorded by the control system of the mock-up, while the deviation ε was determined, which made it possible to identify an emergency, such as “the rope slipping”.

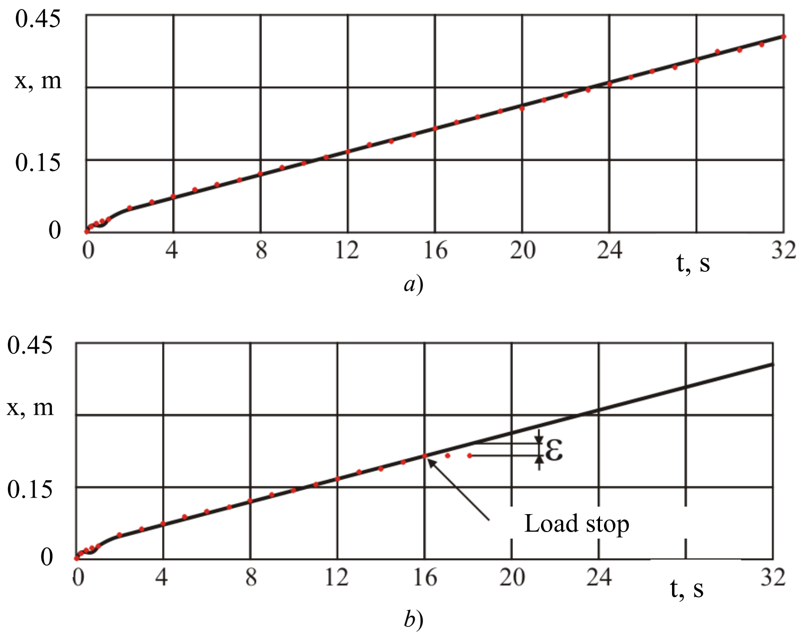

Fig. 7. Simulation results using a digital twin: *(a)* normal movement; *(b)* case of forced rope stop; —— is simulation results; ● is experimental values

Discussion and Conclusions. The application of the considered methodology for creating digital twins has provided the identification of deviations from correct operation to prevent non-routine events and emergencies as in the case of a full-scale ropeway model. In the course of further research, an industrial digital twin of a mobile transport and transshipment rope complex based on the considered methodology will be created. In this case, of emergency situation models will be built.

References

1. Lagerev AV, Lagerev IA, Korotkii AA, et al. Kontseptsiya innovatsionnoi sistemy gorodskogo transporta «Kanatnoe metro goroda Bryanska» [Concept of the innovative system of urban transport "Cable metro of Bryansk city"]. The Bryansk State University Herald. 2012;3:12–15. (In Russ.)

2. Korotkii AA, Lagerev AV, Meskhi BCh, et al. Transportno-logisticheskie tekhnologii i mashiny dlya tsifrovoi urbanizirovannoi sredy [Transport and logistics technologies and machines for digital urbanized environment]; Lagerev AV (ed.). Rostov-on-Don: DSTU Publ. Centre; 2019. 268 p. (In Russ.)

3. Korotkii AA, Lagerev AV, Meskhi BCh, et al. Razvitie transportnoi infrastruktury krupnykh gorodov i territorii na osnove tekhnologii kanatnogo metro [Development of transport infrastructure of large cities and territories on the basis of cableway technology]. Rostov-on-Don: DSTU Publ. Centre; 2017. 344 p. (In Russ.)

4. Kudakaev TZ. Ispol'zovanie gruzovykh kabel'-kranov dlya raboty v slozhnykh usloviyakh. Opyt primeneniya v Rossii [Use of cargo cable cranes for operation under close conditions. Application experience in Russia]. Territory Engineering. 2014;5:62–67. (In Russ.)

5. D'yachkova OM, Volod'kin PP. Sfery primeneniya gorodskogo passazhirskogo transporta [The scope of application of urban passenger transport]. Uchenye Zametki TOGU. 2013;4(4):1492–1501. URL: http://pnu.edu.ru/ejournal/pub/issues/14/ (accessed: 29.08.2020). (In Russ.)

6. Lagerev AV, Tarichko VI, Soldatchenkov SP. Obespechenie obshchei ustoichivosti bazovykh kolesnykh stantsii mobil'nykh kanatnykh dorog [General stability of a base vehicle of a mobile ropeway]. Scientific and Technical Journal of Bryansk State University. 2019;2:210–220. (In Russ.)

7. Norenkov IP. Avtomatizirovannye informatsionnye sistemy: uchebnik dlya vuzov [Automated information systems]. Moscow: Bauman University Publ. House; 2011. 344 p. (In Russ.)

8. Kokorev DS, Yurin AA. Tsifrovye dvoiniki: Ponyatie, tipy i preimushchestva dlya biznesa [Digital twins: concept, types and benefits for business]. Colloquium-journal. 2019;10-2:101–104. (In Russ.)

9. Vasil'ev AN, Tarkhov DA, Malykhina GF. Metody sozdaniya tsifrovykh dvoinikov na osnove neirosetevogo modelirovaniya [Methods of creating digital twins based on neural network modeling]. Modern Information Technologies and IT-Education. 2018;14(3):521–532. (In Russ.)

10. Tarichko VI, Khimich AV. Kompleksnaya matematicheskaya model' mobil'nogo transportno-peregruzochnogo kanatnogo kompleksa [Comprehensive model of the mobile transport and overloading ropes complex]. Scientific and Technical Journal of Bryansk State University. 2019;4:523–532. (In Russ.)

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Claimed contributorship

I. A. Lagerev: general concept development; scientific editing; the text revision; the text layout. V. I. Tarichko: creation of a 3D model of the mobile ropeways and a full-scale experiment; preparation of materials for the manuscript. A. V. Panfilov: development of a mathematical model of a digital twin of the mobile ropeways; preparation of materials for the manuscript.

All authors have read and approved the final manuscript.